Isospin Dependence of Pion Absorption on a Pair of Nucleons

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The relative cross sections for the $2N + \pi \rightarrow 2N$ reactions were determined where the initial two nucleons are in a relative s state, and coupled either to isospin zero or to one. This information is extracted from two-nucleon coincidence measurements of the $(\pi^+, 2p)$ and the (π^-, pn) reactions on targets of ^{3}He and ^{4}He.

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Pion absorption is usually treated as proceeding through the $\pi + 2N \rightarrow 2N$ process. Considerable effort[1] has been devoted to understanding the $\pi^+ + d \rightarrow pp$ reaction, in which absorption takes place on a $T = 0$, $S = 1$ nucleon pair. At bombarding energies in the (3,3) resonance region this reaction is believed to be dominated by the intermediate ΔN configuration with $(J^\pi)_{\Delta N} = 2^+$ and ΔN orbital angular momentum $L_{\Delta N} = 0$. Much less consideration has been given to the analogous process in which the pion is absorbed by two nucleons in a $T = 1$, $S = 0$ state. Such nucleon pairs are present in all nuclei heavier than the deuteron, and understanding absorption on such pairs is important to the understanding of nuclear pion absorption in general. The inverse of this process certainly does play a role in pion production ($N_A + N_B \rightarrow N_C + N_D + \pi$) and is part of the cross sections designated as σ_{11} and σ_{01} in the traditional parametrization.[2] In pion production, however, several partial waves may contribute, and there is no simple way to select the piece of the cross section in which the $(N_C N_D)$ pair is restricted to $J^\pi = 0^+$, $T = 1$.

If one assumes Δ dominance in the absorption process then it follows that the reaction $\pi + 2N \rightarrow 2N$ can only go through a $T = 1$ final state. If only isospin is considered, absorption on an initially $T = 0$ nucleon pair is twice as likely as that on an initially $T = 1$ pair.[3] It should be noted, however, that absorption on an initial $J^\pi = 0^+$, $T = 1$ pair involves intermediate states that are *different* from the $T = 0$ case, as may be seen in Table I. In particular, $L_{\Delta N} = 0$, which dominates absorption on a deuteron, is not allowed in the $T = 1$ case. Thus more detailed dynamical considerations may very well enter in this ratio.

In the present work we report on coincidence measurements of the $\pi + 2N \rightarrow 2N$ process with targets of ^{4}He and ^{3}He. We assume ^{4}He and ^{3}He to have simple wave functions with all particles in relative s states, so that a comparison of the $(\pi^+, 2p)$ and the (π^-, pn) reactions will be simply related to the isospin cross sections; the former must start with an initial pair of (np) nucleons that could be in either a $T = 1$ or a $T = 0$ state, while the latter *must* start with the initial pair of $T = 1$ protons.

The experiment was performed with 165-MeV pion beams from the P^3 channel of the Los Alamos Meson Physics Facility. Cryogenic liquid targets were used, with thicknesses of 343 and 629 mg/cm^2 for ^{3}He and ^{4}He, respectively.[4] Protons were detected with a magnetic spectrometer,[5] with a momentum acceptance $\Delta p/p = \pm 25\%$ and solid angle of 8 msr. Coincident protons and neutrons were

TABLE I. Quantum numbers permitted in the Δ model for $\pi + (2N)_i \rightarrow (2N)_f$.

J_i^π, $L_i = 0$ T_i	$L_{(\pi-2N)}$ [a]	$J_{\Delta N}^\pi$, $L_{\Delta N}$ [a] $T_{\Delta N} = 1$	$J_f^\pi (= J_{\Delta N}^\pi)$, L_f [a] $T_f (= T_{\Delta N}) = 1$
$J_i^\pi = 1^+$	0	1^-, 1	1^-, 1
$T_i = 0$	1	0^+, 2	0^+, 0
		2^+, 0, or 2	2^+, 2
	2	1^-, 1	1^-, 1
		2^-, 1	2^-, 1
$J_i = 0^+$	0	0^-, 1	0^-, 1
$T_i = 1$	2	2^-, 1	2^-, 1

[a] Only $L \leq 2$ is listed.

detected with two 6 in. deep × 6 in. wide × 14 in. high plastic scintillators 63 in. from the target. Thin scintillators in front of these detectors served to separate neutrons from charged particles. The neutron detection efficiency was determined by measuring coincident neutrons from the $\pi^- d \to nn$ reaction and was $(15 \pm 2)\%$ for 150-MeV neutrons, and the energy dependence of the efficiency over the pertinent energy range was also calculated.[6] The solid angle was defined by the $4° \times 4°$ acceptance of the magnetic spectrometer. For each coincident event, pulse heights and times of flight to the scintillators as well as the momentum measured by the spectrometer were recorded. The beam was monitored by a pair of decay-muon detectors positioned on either side of the beam axis. Both monitors were calibrated by measuring the π-p scattering differential cross section.

Measurements were performed with the spectrometer set at 55° and 75° (and for ^{4}He also 110°) relative to the beam axis. The scintillators were positioned at − 75° and − 100° (and for the 110° measurement at − 45° and − 70°). The angles were chosen so that one detector was positioned at the conjugate angle for the $\pi + d \to 2N$ process, and the second detector 25° away. The angular correlation is expected to be smeared out around the conjugate angle, for both ^{4}He and ^{3}He, because of the internal momenta of the nucleons.

As shown in Fig. 1 the direct absorption on a pn pair in the $(\pi^+, 2p)$ reaction is clearly observed as a strong peak over the three- and four-body breakup phase space, for the detector positioned at the conjugate angle. After subtraction of the data in the nonconjugate angle a direct two-nucleon absorption yield was established. This subtraction does not alter the yield substantially, since the quantity subtracted was small, as may be seen in Fig. 1, and was a similar fraction of the yield for (π^-, pn). Exactly the same procedure was followed under identical conditions for the subtraction for π^+ and π^-; the data for conjugate and nonconjugate angles were taken simultaneously with identical detectors. The subtraction was meant as a correction for possible three- and four-body processes, although the "nonconjugate" yield also includes the tail of the two-body process, broadened in angle by the internal momentum of the pair (more for ^{4}He than for ^{3}He). The direct two-nucleon absorption for (π^-, pn) was very weak, as may be seen in Fig. 2. Yields with the cryostats empty were < 1% of the yields with He.

The ratios $R \equiv d\sigma(\pi^-, pn)/d\sigma(\pi^+, pp)$ in Table II

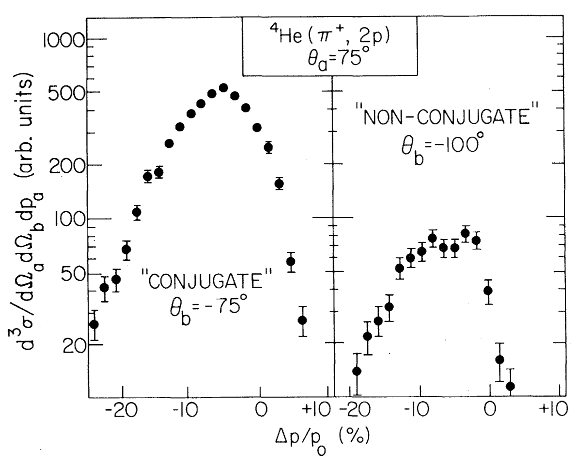

FIG. 1. Momentum spectra of protons detected with the magnet at 75° and 165-MeV π^+ incident on a ^{4}He target. The left-hand curve is for coincidences with a scintillator at -75° (the conjugate angle for $\pi + d \to 2p$) and the right-hand curve for another identical scintillator at $\theta = -100°$. The two sets of data are presented with the correct relative normalization.

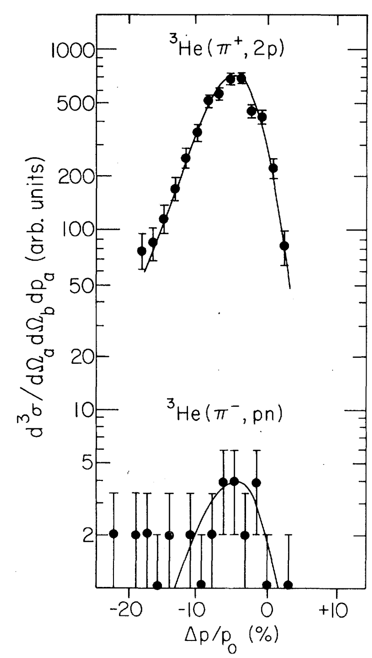

FIG. 2. Momentum spectra of protons detected with the magnet at 55° with 165-MeV pions incident on a ^{3}He target. The upper curve was taken with π^+ and protons in coincidence in a scintillation arm at -100°; while the lower curve is with π^- and neutrons in coincidence. The two sets of data are presented with the correct relative normalization.

TABLE II. Ratios $R \equiv d\sigma(\pi^-, np)/d\sigma(\pi^+, pp)$.

θ_a, θ_b [a]	Target	$10^2 R$ [b]	$10^2 \frac{d\sigma(T_i=1)}{d\sigma(T_i=0)}$	$10^2 \left\langle \frac{d\sigma(T_i=1)}{d\sigma(T_i=0)} \right\rangle_{\rm Av}$
55°, −100°	^{3}He	1.02 ± 0.27	3.1 ± 0.8	3.0 ± 0.8
55°, −100°	^{4}He	0.42 ± 0.32	2.5 ± 1.9	
75°, −75°	^{3}He	0.48 ± 0.35	1.4 ± 1.1	1.8 ± 1.0
75°, −75°	^{4}He	0.55 ± 0.38	3.3 ± 2.3	
110°, −45°	^{4}He	0.40 ± 0.26	2.4 ± 1.6	
55°, −100°	^{12}C	$\lesssim 2.0$		

[a] Laboratory angles for the spectrometer (θ_a) and the conjugate scintillation detector (θ_b).

[b] This ratio is that of cross sections for detecting *two* protons in coincidence compared to a neutron-proton pair.

take into account the fact that for p-p coincidence both detectors can detect either particle, while for p-n coincidences neutrons may be detected only by the scintillator and protons only by the magnet. The (π^-, pn) cross sections are very small; only the 55° measurement on ^{3}He provides a value for the ratio that is clearly greater than zero. The absorption cross sections may be written for $\pi^+ + np \to pp$ [or (π^+, pp)] as

$$d\sigma_{(\pi^+, pp)} = \sum_{T_i = 0,1} \langle 1\,1\,T_i\,0 | 1\,1 \rangle^2 N_{T_i}{}^{np} d\sigma_{T_i}$$

and for $\pi^- + pp \to np$ [or (π^-, np)] as

$$d\sigma_{(\pi^-, np)} = \langle 1\,-1\,1\,1 | 1\,0 \rangle^2 N_{T_i=1}{}^{pp} d\sigma_{T_i=1},$$

where σ_{T_i} is the absorption cross section for the initial nucleon pair (in a relative s state) with isospin T_i, and $N_{T_i}{}^{np}$ and $N_{T_i}{}^{pp}$ are the number of possible nucleon pairs with isospin T_i in the target nucleus: $N_0{}^{np}$ is 3 and 1.5 for ^{4}He and ^{3}He, respectively, $N_1{}^{np} = 1$ and 0.5, and $N_1{}^{pp} = 1$ for both. [Note that σ_1 is *not* to be confused with the traditional σ_{11} or σ_{01} of Ref. 2, since in the present work the initial pair is always assumed to be in an s state. On the other hand, our σ_0 *is* related by detailed balance to $\sigma_{10}(d)$, except for differences between the deuteron wave function and those of (np), $J^\pi = 1^+$, $T = 0$ pairs in ^{3}He or ^{4}He.] Thus we have

$$R(^4\text{He}) \equiv \frac{d\sigma(\pi^-, np)}{d\sigma(\pi^+, pp)} = \frac{0.5 d\sigma_1}{3 d\sigma_0 + 0.5 d\sigma_1},$$

or

$$\frac{d\sigma_1}{d\sigma_0} = \frac{6R(^4\text{He})}{1 - R(^4\text{He})},$$

and

$$R(^3\text{He}) = \frac{0.5 d\sigma_1}{1.5 d\sigma_0 + 0.25 d\sigma_1},$$

or

$$\frac{d\sigma_1}{d\sigma_0} = \frac{6R(^3\text{He})}{2 - R(^3\text{He})}.$$

For $d\sigma_1/d\sigma_0 = \frac{1}{2}$ one would have expected $R(^4\text{He}) = \frac{1}{13}$, and $R(^3\text{He}) = \frac{2}{13}$. We may solve for $d\sigma_1/d\sigma_0$ for each measurement; these numbers are included in Table II, and are averaged at each angle. It is clear that the cross section for $T = 1$ is very much smaller than the value one would have expected from isospin considerations alone—the dynamical suppression (presumably, at least in part, due to the fact that $L_{\Delta N} = 0$ is forbidden in the intermediate state) is at least another order of magnitude. Considering the effort that has gone into gaining a theoretical understanding of the $\pi + d \to 2N$ system[1] one may hope that some attention may be spared for the conjugate process. The angular distributions for the two isospins need not be the same since the intermediate angular momenta are different, as was shown in Table I, and can give rise to different shapes. The ratio R is similarly small for the one measurement that we carried out for a heavier target, ^{12}C.

It appears then that the $\pi + 2N \to 2N$ process is strongly suppressed when the initial nucleon pair is in a $T = 1$, $S = 0$ state, by much more than the factor of $\frac{1}{2}$ that had been assumed in the interpretation of inclusive (π, p) spectra.[3,7] For ^{4}He, for instance, the ratio of energetic protons in singles proton spectra from $^4\text{He}(\pi^-, p)X$ to those from $^4\text{He}(\pi^+, p)X$ was said to be consistent with $\frac{1}{21}$ (or $\frac{1}{27}$) expected from this factor of $\frac{1}{2}$.[7] It is now clear that, although the singles data may be consistent with such a ratio, the energetic protons from $^4\text{He}(\pi^-, p)$ are primarily from a more complicated process. The difference in wave functions between the deuteron and ^{4}He does not seem to alter the cross sections appreciably: The relative magnitudes of the (π^+, p) cross sections are in agreement with the ratio 3:1 expected if the $\pi^+ + pn \rightarrow 2p$ process dominates. (At $T_\pi = 160$ MeV the observed ratio was 3.0 ± 0.5.[7]) In heavy nuclei it has been assumed that the π^-/π^+ ratios for energetic protons from the $(\pi, 2N)$ mechanism would approach $\sim \frac{1}{11}$.[7] It seems that a more appropriate value for heavy nuclei is $\approx \frac{1}{100}$; in other words most of the energetic protons produced by π^- cannot be assumed to originate from a simple $\pi + 2N \rightarrow 2N$ process. Our result is consistent with the recent observation that the $(\pi, 2N)$ reaction on ^{12}C and ^{32}S does not excite $J = 0^+$, $T = 1$ states in ^{10}B or ^{30}P.[8]

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[1]For some recent work, see A. W. Thomas and A. S. Rinat, Phys. Rev. C 20, 216 (1979); J. Chai and D. O. Riska, Nucl. Phys. A329, 429 (1979); M. Betz and T. S. H. Lee, Phys. Rev. C 23, 375 (1981), and references therein.

[2]A. H. Rosenfeld, Phys. Rev. 96, 139 (1954); M. Gell-Mann and K. M. Watson, Annu. Rev. Nucl. Sci. 4, 219 (1954); S. Mandelstam, Proc. Roy. Soc. London, Ser. A 244, 491 (1958).

[3]See, for instance, J. N. Ginocchio, Phys. Rev. C 17, 195 (1978); this result comes from the ratio of the squares of the isospin coupling coefficients $\langle \frac{1}{2}, (\frac{1}{2}\,1)_{3/2}; 1 | (\frac{1}{2}\,\frac{1}{2})_{T_i}, 1; 1 \rangle$ for $T_i = 0$ and 1.

[4]J. S. McCarthy, I. Sick, and R. R. Whitney, Phys. Rev. C 15, 1396 (1977).

[5]E. P. Colton, Nucl. Instrum. Methods 178, 95 (1980).

[6]R. J. Kurz, University of California Radiation Laboratory Report No. 11339, 1964 and 1965 (unpublished).

[7]H. E. Jackson *et al.*, Phys. Rev. Lett. 39, 1601 (1977); H. E. Jackson *et al.*, Phys. Rev. C 16, 730 (1977); R. D. McKeown *et al.*, Phys. Rev. Lett. 44, 1033 (1980); R. D. McKeown *et al.*, Phys. Rev. C 24, 211 (1981).

[8]C. E. Stronach *et al.*, Phys. Rev. C 23, 2150 (1981).

Microscopic Dynamical Calculation of Nucleon Flow in Heavy-Ion Reactions

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The nucleon exchange process in deep-inelastic collisions is investigated by studying the one-way current constructed using the Wigner transform of the time-dependent Hartree-Fock one-body density matrix. Detailed calculations for head-on ^{16}O + ^{16}O collisions at three different bombarding energies have been performed. A combination of two simple models for the contributions from relative motion and tunneling is shown to predict one-way currents close to the time-dependent Hartree-Fock results.

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Many characteristics of heavy-ion reactions are known to be strongly influenced by the exchange of nucleons between the colliding partners.[1] Within the framework of a quantum statistical approach, various diffusion models have been put forth to describe such nucleon transfers.[2] In

